12-2000

Managing a Flow Line with Single-Kanban, Dual-Kanban or Conwip

Kum Khiong YANG

Singapore Management University, kkyang@smu.edu.sg

DOI: https://doi.org/10.1111/j.1937-5956.2000.tb00463.x

Published in Production and Operations Management, Volume 9, Issue 4,
December 2000, Pages 349-366.
http://doi.org/10.1111/j.1937-5956.2000.tb00463.x

MANAGING A FLOW LINE WITH SINGLE-KANBAN, DUAL-KANBAN OR CONWIP*

KUM KHIONG YANG
Singapore Management University, Singapore

To control the production of different parts on a single flow line, managers can choose between the Single-kanban, Dual-kanban, and Conwip. This paper therefore compares the three different systems. The results show that Conwip consistently produces the shortest mean customer wait time and lowest total work-in-process. Our results also contradict the finding of a previous study, which showed that Dual-kanban performed better than Single-kanban. The different findings can, however, be attributed to the use of a material transfer policy, which favors the Dual-kanban modeled in the previous study. Our study shows that transferring replenished containers immediately to downstream stations, increasing the number of cards, and reducing the withdrawal cycle reduce the mean customer wait time significantly.
(PRODUCTION CONTROL SYSTEMS; SINGLE-KANBAN; DUAL-KANBAN; CONWIP; SIMULATION)

1. Introduction

During the last two decades, there has been much interest in the development and use of simple production control systems such as Single-kanban, Dual-kanban, and Conwip. While various authors such as Schonberger (1982), Monden (1983), and Hopp and Spearman (1996) have discussed the different systems, no study has systematically compared the different systems for managing a multi-product flow line.

A review of the literature shows that the studies on Kanban and Conwip can be divided into a framework proposed in Table 1. While many studies have examined the Kanban and Conwip, no study has rigorously compared the different systems in a single study for managing a multi-product flow line. Berkley and Kiran (1991), for example, examined only a Dual-kanban multi-product flow line. They compared policies on the withdrawal cycles and priority rules, and found that first-come, first-served (FCFS) priority rule produces a shorter mean customer wait time and lower total work-in-process than the shortest processing time (SPT) priority rule.

In another study, Berkley (1993) extended the study by Berkley and Kiran (1991). He showed that FCFS produces a higher production rate than SPT in a Single-kanban flow line. Berkley (1993) also compared the performance of a Single-kanban and a Dual-kanban flow line. Unfortunately, he used a material transfer policy that favors the Dual-kanban by allowing full containers with withdrawal kanbans to move downstream immediately. How-

TABLE 1
Classification of Past Research

Type of Flow Line	Type of Control Systems Examined		
	Kanban	Conwip	Kanban and Conwip
Single-product			Spearman and Zazanis (1992) Muckstadt and Tayur (1995a) Muckstadt and Tayur (1995b)
Multi-product	Berkley and Kiran (1991) Berkley (1993) Ardalan (1997)		Spearman, Woodruff, and Hopp (1990) This research

ever, when the Single-kanban was used, he allowed the full containers to move downstream only periodically. His study therefore provided a biased comparison between the Single-kanban and Dual-kanban flow lines, suggesting a need for further analysis.

In another study, Ardalan (1997) examined four policy variables for managing a Dual-kanban flow line that produces six different parts. The policies examined include the priority rules, withdrawal cycles, status of the waiting withdrawal cards, and number of cards. He found that using information on the waiting withdrawal cards reduces both the mean customer wait time and total work-in-process.

In a paper that won the J.D. Scaife Award, Spearman, Woodruff, and Hopp (1990) proposed Conwip as an alternative to the Kanban. They, however, discussed the advantages of Conwip without any rigorous comparison with the Kanban.

In view of the above studies that have not rigorously compared the Kanban and Conwip, the question remains on which is the best system for managing a multi-product flow line. For a flow line that produces a single part type, Spearman and Zazanis (1992) have shown that Conwip produces a higher mean throughput than Kanban, while Muckstadt and Tayur (1995a, 1995b) have shown that Conwip produces a less variable throughput and a lower maximum inventory than Kanban. These results are, however, proven for a single-product flow line and should be used with care for a multi-product flow line. In their conclusions comparing Kanban and Conwip, Muckstadt and Tayur (1995b) also suggested the need for future work dealing with the “demand variation and correlation aspects in a multi-product setting.”

The purpose of this paper is to extend the previous studies by comparing Kanban and Conwip in a multi-product flow line using computer simulation. The results offer several important extensions of the previous studies. First, by comparing the Single-kanban, Dual-kanban, and Conwip in a single study, this paper offers managers a better understanding of choosing the right production control system for a multi-product flow line. This contribution is significant because no previous study has rigorously compared the different systems or provided the insights on choosing the right system for a multi-product flow line.

Second, the policy variables that affect the performance of the production control systems are examined. These policies include the priority rules, number of cards, withdrawal cycles, and transfer policies. By studying the policy variables and production control systems together, this paper provides important insights on the interactions between the policy variables and production control systems. These results will help managers in choosing the right policy variables, considering their full interactions with one another.

Third, this paper examines three additional performance measures that were not examined in previous studies. These measures are the number of upstream trips, number of downstream trips, and total number of trips between stations. By examining the number of upstream and downstream trips, this study provides new insights on the tradeoff between customer service and the number of trips between stations.

The remaining sections of this paper are organized as follows. In Section 2, we describe a simulation model of a five-station, six-product flow line. We then describe the Single-kanban, Dual-kanban, and Conwip in Section 3. In Sections 4 and 5, we present the four policy variables and the performance measures, respectively. Next, we propose a simulation experiment and analyze the simulation results. Finally, the conclusions discuss the managerial implications and directions for future research.

2. A Multi-Product Flow Line

A review of the past literature showed that a five-station flow line is adequate in representing the various hypothetical and real flow lines cited in the literature. These cited flow lines vary from 5 to 7 stations manufacturing 4 to 10 different parts on a single line (Berkley and Kiran 1991; Berkley 1993; Ardalan 1997). To compare the Single-kanban, Dual-kanban, and Conwip, this study therefore models a five-station flow line that produces six different parts using SLAM II (Pritsker 1986). The modeled flow line is similar to the flow line used by Ardalan (1997), who provided further justification and examples of similar flow lines used in real companies.

The five-station flow line is modeled such that the demand for parts is triggered by the arrivals of customers' orders. Each order is a request for one full container of a specific part selected randomly from six different parts, and each full container of a part requires processing through the flow line from the first station to the last station.

To further model the common practice of Just-in-Time production, this study assumes that customers' orders arrive directly at the last station and the last station begins production only after the receipt of a customer's order. The last station therefore maintains a back-order list of customers' orders for different parts. It also maintains an input storage point for the storage of full containers of raw materials produced by the station immediately upstream. Whenever the last station becomes idle, its station operator will choose, from the back-order list, orders that have a full container of the corresponding raw materials at the last station's input storage point. Among these orders, the station operator will choose and process the order that has waited the longest. At the start of each processing of a new order, the station operator will open a new full container of raw materials at the last station, remove the withdrawal card that is attached to the full container of raw materials, and post the card on the last station's outgoing withdrawal card post. A material handler will then periodically visit the last station and move the outgoing withdrawal cards upstream.

While the production at the last station is driven by the customers' orders for different parts, the Single-kanban, Dual-kanban, or Conwip can be used to manage the production and movement of parts through the five-station flow line. The stations are operated such that each station $i+1$ withdraws its raw materials from the next upstream station i. Each station also maintains one input and one output storage point for the storage of full containers of raw materials and finished parts, respectively.

To maintain a certain level of consistency with the past studies (Berkley and Kiran 1991; Berkley 1993; Ardalan 1997), three additional assumptions are made on the operations of the flow line. First, the first station is assumed to have an infinite supply of raw materials and is never starved of raw materials. Second, exponential distributions are used to generate the order interarrival and container processing times. This assumption is supported by the results of Berkley (1993). His results showed that the use of two different distributions (normal and exponential) does not affect the ranking of most policy variables such as the number of cards and withdrawal cycle. Although his results showed that the relative rankings of the priority rules are affected, their absolute differences are negligible. Third, the mean utilization of the flow line is assumed and fixed at 70%. This assumption follows the mean utilization levels observed in practice by Wemmerlov and Hyer (1989). The mean order interarrival time and mean processing time of each container at each station are therefore fixed at 1.4286 and 1.0 periods, respectively.

3. Production Control (PC) Systems

This paper compares the performance of three alternative production control systems for managing the production and movement of parts on a multi-product flow line. While the three systems do share some common characteristics on the use of cards to authorize the production and movement of parts from one station to another, they are distinctively different in the detailed implementation. Two basic types of cards are used. The Single-kanban and Conwip use only withdrawal cards, while the Dual-kanban uses both production and withdrawal cards.

3.1. *Single-Kanban* (*SK*) *System*

The Single-kanban uses only withdrawal kanbans (or cards). Each withdrawal card is used to communicate the need to produce and transfer a full container of raw materials for a specific part from an upstream station i to the next downstream station $i + 1$. With the exception of the last station, which has one outgoing withdrawal card post, each remaining station has one incoming and one outgoing withdrawal card post for the storage of incoming and outgoing withdrawal cards, respectively.

Periodically, a material handler will remove all the withdrawal cards from the outgoing withdrawal card post of station $i + 1$ and bring these withdrawal cards upstream to station i. Maintaining the withdrawal cards in the same order as they are posted on the outgoing withdrawal card post of station $i + 1$, the material handler will post the cards on the incoming withdrawal card post of station i. The material handler will then gather all full containers that are attached with withdrawal cards at the output storage point of station i, and carry them back to the input storage point of station $i + 1$.

In addition, whenever a station i becomes idle, its station operator will choose and produce a part requested by the withdrawal cards posted on the station i's incoming withdrawal card post. If the incoming withdrawal card post is empty or if the incoming withdrawal cards require raw materials that are not available at the station i's input storage point, the station i will remain idle. Otherwise, the station operator will use a priority rule to select a withdrawal card from the station i's incoming withdrawal card post for production. At each station i, the production of a part can be started only if a withdrawal card for that part is posted on the station's incoming withdrawal card post and a full container of raw materials for that part is available at the station's input storage point. The station operator will then detach the withdrawal card that is attached to the full container of raw materials and post the card on the station's outgoing withdrawal card post.

When a full container of a part is completed at station i in response to a chosen incoming withdrawal card, the chosen withdrawal card is removed from the station i's incoming withdrawal card post and attached to the full container of the completed part. The full container with the newly attached withdrawal card can then be transferred to the downstream station $i + 1$ either immediately or at the next withdrawal cycle, depending on the chosen transfer policy. The different transfer policies are described in Section 4.4, and each transfer policy defines a way for handling the containers replenished between the periodic withdrawal cycles. The withdrawal cycle is the time interval between the alternate visits by the material handler to move withdrawal cards upstream and replenished containers (with attached withdrawal cards) downstream.

3.2. *Dual-Kanban* (*DK*) *System*

The Dual-kanban uses two types of kanbans (or cards). A production card is used to authorize the production of one full container of a part at a station, while a withdrawal card is used to authorize the transfer of one full container of raw materials for a part from an upstream station i to the next downstream station $i + 1$. With the exception of the last station, which has one outgoing withdrawal card post, the Dual-kanban requires one production card post, one incoming withdrawal card post, and one outgoing withdrawal card post for each station. These card posts are used for storing the production, incoming withdrawal, and outgoing withdrawal cards, respectively.

Periodically, a material handler will remove all the withdrawal cards posted on the outgoing withdrawal card post of station $i + 1$ and bring the withdrawal cards to the output storage point of station i. While moving the withdrawal cards from station $i + 1$ to station i, the material handler is assumed to maintain the withdrawal cards in the same order as they are posted on the outgoing withdrawal card post of station $i + 1$.

At station i, the material handler will search for parts requested by the withdrawal cards brought over from station $i + 1$. If a full container of a requested part is available at the output storage point of station i, the material handler will detach the production card that is attached to the full container, and post the production card on the station i's production card post. For each full container with a detached production card, the material handler replaces the detached production card with the corresponding withdrawal card. When several production cards are removed, the production cards are also posted on the station i's production card post in the same order as they are removed from the full containers of parts. If the parts corresponding to the incoming withdrawal cards are not available at the output storage point of station i, the withdrawal cards are posted on the station i's incoming withdrawal card post. These withdrawal cards represent parts that cannot be satisfied immediately from the output storage point of station i. The material handler will then carry the full containers with attached withdrawal cards from the output storage point of station i back to the input storage point of station $i + 1$.

Whenever a station i becomes idle, its station operator will choose and produce a part requested by the withdrawal or production cards posted on the station i's incoming withdrawal and production card posts. Since the withdrawal cards on the incoming withdrawal card post represent requests to transfer parts to the downstream station $i + 1$, these withdrawal cards represent orders that are more urgent than the production cards. The Dual-kanban modeled in this study, therefore, follows Ardalan's (1997) recommendation to produce parts requested by the incoming withdrawal cards before those requested by the production cards. However, if the incoming withdrawal card post is empty or if the incoming withdrawal cards require raw materials that are not available at the station i's input storage point, the station operator will choose and produce parts requested by the production cards posted on the station i's production card post. Ardalan (1997) has shown that his recommendation reduces both the mean customer wait time and total work-in-process simultaneously.

At each station i, the production of a part can be started only if the part is requested by an incoming withdrawal (or production) card and a full container of raw materials for that part is available at the station i's input storage point. When a part is chosen for production, the station operator will immediately remove the withdrawal card that is attached to the full container of raw materials, and post the card on the station i's outgoing withdrawal card post.

When a full container of a part is completed at station i in response to an incoming withdrawal card, the station operator will remove the chosen incoming withdrawal card from the incoming withdrawal card post and attach the withdrawal card to the full container. The full container with the newly attached withdrawal card can then be transferred to the downstream station $i + 1$ either immediately or at the next withdrawal cycle, depending on the chosen transfer policy described in Section 4.4. However, when a full container of a part is completed in response to a production card, the station operator will remove the chosen production card from the production card post and attach the production card to the full container. The full container with the newly attached production card is then stored at the output storage point of station *i*.

3.3. *Conwip* (*CW*) *System*

The idea of constant work-in-process (Conwip) was first proposed by Spearman, Woodruff, and Hopp (1990). In their paper, they proposed a system that can dynamically assign the withdrawal cards to produce different parts. In contrast, a typical Kanban system uses only part-specific withdrawal cards. Consequently, to maintain a fairer comparison between Conwip and Kanban, we modeled a Conwip system that also uses part-specific withdrawal cards. However, unlike the Kanban systems that circulate each withdrawal card between alternate stations, Conwip allows each withdrawal card to circulate through the entire flow line. Conwip also requires only two card posts for the entire flow line; one outgoing withdrawal card post for the last station and one incoming withdrawal card post for the first station.

Periodically, a material handler will remove and bring all the withdrawal cards from the outgoing withdrawal card post of the last station to the first station. Maintaining the withdrawal cards in the same order as they are posted on the outgoing withdrawal card post of the last station, the material handler will post the cards on the incoming withdrawal card post of the first station. The material handler will then gather all the full containers that are attached with withdrawal cards at the output storage point of the first station and transfer them to the input storage point of the second station. The material handler will then continue to transfer all full containers with attached withdrawal cards from the output storage point of station i to the input storage point of station $i + 1$ until the input storage point of the last station is replenished.

In addition, whenever the first station (station 1) becomes idle, the station operator will choose and produce a part requested by the withdrawal cards posted on the station 1's incoming withdrawal card post. Station 1 will remain idle only if its incoming withdrawal card post is empty. Otherwise, a priority rule is used to choose a withdrawal card from the station 1's incoming withdrawal card post for production. When a full container of a part is completed at station 1, the chosen withdrawal card is removed from the station 1's incoming withdrawal card post and attached to the full container. The full container with the newly attached withdrawal card can then be transferred from station 1 to the input storage point of station 2 either immediately or at the next withdrawal cycle, depending on the chosen transfer policy.

At each station between the first and the last station, Conwip uses a "push" philosophy to process each full container of raw materials. At each station, the station operator will continually process each full container of raw materials at its input storage point until its input storage point is empty. When there are more than one full container of raw materials at an input storage point, a priority rule is used to select the full container of raw materials to process next. Upon the completion of each full container at station i, the full container with the attached withdrawal card is transferred to the input storage point of station $i + 1$ either immediately or at the next withdrawal cycle, depending on the chosen transfer policy described in Section 4.4.

4. Policy Variables

Besides the above production control systems, this study examines four other policy variables.

4.1. *Priority Rules* (*PR*)

When a station becomes idle and several cards compete for the same station, the station operator uses a priority rule to select the production or withdrawal card to process next. Two priority rules are examined. The FCFS priority rule gives priority to the card that has waited the longest, while the maximum number of cards (MNC) priority rule gives priority to the card that has the largest number of cards waiting for the same part.

When choosing a card (or part) for production at a station, the station operator must choose only from cards that have a full container of the corresponding raw materials at the station's input storage point. When the Single-kanban is used, the station operator will use a priority rule to choose from the station's incoming withdrawal card post. When the Dual-kanban is used, the station operator chooses first from the incoming withdrawal card post. However, if the incoming withdrawal card post is empty or if the raw materials required by the incoming withdrawal cards are not available at the station's input storage point, the station operator will then choose a card from the production card post. This implementation of the priority rules follows Ardalan's (1997) recommendation. When Conwip is used, the operator at the first station will choose from its incoming withdrawal card post using either the FCFS or MNC priority rule. At the other stations between the first and the last station, the station operators will choose and process each full container of raw materials (with an attached withdrawal card) using the same priority rule used by the first station.

4.2. *Number of Cards* (*NC*)

This study examines the total number of cards per part for the five-station flow line at two levels: small and large. For both the Single-kanban and Dual-kanban, a total of 8 and 16 cards per part are used at the small and large number of cards, respectively. Since there are 4 interacting pairs of stations along the 5-station flow line, these 2 levels of cards correspond to 2 cards (i.e., 8 cards/4 interfaces) and 4 cards (i.e., 16 cards/4 interfaces) per part for each pair of stations. To communicate the need for a part between two stations, the Single-kanban therefore uses two and four withdrawal cards per part for the small and large number of cards, respectively. Correspondingly, between two alternate stations, the Dual-kanban uses one production and one withdrawal card per part for the small number of cards, and two production and two withdrawal cards per part for the large number of cards.

While our original intention was to use the same total number of cards for the Single-kanban, Dual-kanban, and Conwip, trial simulation showed that Conwip consistently produces a substantially shorter mean customer wait time but a slightly higher total work-in-process than the Kanban systems when the same total number of cards is used. This observation suggests that Conwip can simultaneously produce a shorter mean customer wait time and a lower total work-in-process than the Kanban systems if the total number of cards is reduced slightly from the levels used by the Kanban systems. Berkley (1993) and Ardalan (1997), for instance, have shown that reducing the number of cards increases the mean customer wait time but reduces the total work-in-process. Consequently, to emphasize the fact that Conwip can simultaneously produce a shorter mean customer wait time and a lower total work-in-process than Kanban, the total number of cards for Conwip is set at 5 and 10 cards per part for the small and large number of cards (instead of 8 and 16 cards for the Kanban systems). The results (to be discussed in Section 7) will support our contention that Conwip can simultaneously produce a shorter mean customer wait time and a lower total work-in-process than the Single-kanban and Dual-kanban.

4.3. *Withdrawal Cycle* (*WC*)

Withdrawal cycle is the time interval between alternate visits by a material handler to move empty containers and withdrawal cards upstream from one station to another. At the same time points when the empty containers and withdrawal cards are moved upstream, the material handler is also expected to move all full containers (with attached withdrawal cards) downstream from the output storage point of each station i to the input storage point of station $i + 1$.

Both Berkley (1993) and Ardalan (1997) have shown that the withdrawal cycle affects the mean customer wait time and total work-in-process significantly. This study therefore examines three withdrawal cycles of 2, 4, and 6 periods. These values are consistent with those used in the past studies (Berkley and Kiran 1991; Berkley 1993; Ardalan 1997). While the withdrawal cycles are periodic, the actual move times for the upstream and downstream movements between stations are assumed to be instantaneous. Berkley and Kiran (1991) and Berkley (1993) have found that this assumption of zero move times has little impact on the simulation results.

4.4. *Transfer Policy* (*TP*)

When the withdrawal cycles or visits by a material handler at each station are periodic, full containers of parts with attached withdrawal cards can be produced and completed between the alternate visits by the material handler. Two alternative transfer policies are examined for handling the full containers replenished between the alternate visits by the material handler. The immediate transfer (IT) policy transfers each replenished container with an attached withdrawal card immediately to the downstream station $i + 1$, without waiting for the next withdrawal cycle or visit by the material handler. This immediate transfer of the replenished container with the attached withdrawal card can be performed immediately by either the station operator or a material handler summoned immediately by the station operator.

The second transfer policy is the periodic transfer (PT) policy. The periodic transfer policy stores each replenished container with an attached withdrawal card at the output storage point of the producer-station i. At the next withdrawal cycle, the material handler will then transfer all full containers with attached withdrawal cards from station i to station $i + 1$. Intuitively, the PT policy should reduce the number of downstream trips between stations, but increase the mean customer wait time.

5. Performance Criteria

To analyze the possibility of the production control systems and policy variables to perform well in different dimensions, this paper uses different performance measures covering customer service, work-in-process, and material handling. A total of seven performance criteria are examined. These performance criteria are the mean customer wait time (CWT), total work-in-process at the input storage points (IWIP), total work-in-process at the output storage points (OWIP), total work-in-process in the system (TWIP), number of upstream trips (NUT), number of downstream trips (NDT), and total number of upstream and downstream trips (TNT).

CWT measures the level of customer service. It measures the mean customer wait time for the fulfillment of customers' orders for different parts. The next three criteria (IWIP, OWIP, and TWIP) measure the amount of work-in-process generated in the system. The total work-in-process at the input storage points (IWIP) measures the mean total number of full containers at the input storage points of all stations except the first. The first station is assumed to have an infinite supply of raw materials at its input storage point. The total work-in-process at the output storage points (OWIP) measures the mean total number of full containers at the output storage points of all stations except the last. The last station produces containers of parts for waiting customers' orders and carries no inventory at its output storage point. The sum of IWIP and OWIP provides the measure for the total work-in-process in the system (TWIP).

The next three criteria (NUT, NDT, and TNT) measure the amount of material handling for moving the cards and containers between stations. To measure the amount of material handling between stations, NUT measures the number of upstream trips between pairs of stations, while NDT measures the number of downstream trips between pairs of stations. NUT, for example, is computed by summing the total number of upstream trips between pairs of stations and dividing the total by the length of the simulation run. In each upstream trip between a pair of stations, more than one withdrawal card and one empty container may be moved per trip. Similarly, in each downstream trip between a pair of stations, more than one full container (with an attached withdrawal card) may be moved per trip. The total number of trips (TNT) is the sum of NUT and NDT.

6. Experimental Design

A full factorial simulation experiment was conducted to collect data on the performance of the production control systems and policy variables. The three production control systems examined are the Single-kanban, Dual-kanban, and Conwip. The four policy variables examined include two priority rules, two levels of number of cards, three levels of withdrawal cycles, and two transfer policies. The proposed experiment is summarized in Table 2.

The batch mean method was used to produce 10 replications for each of the $3 \times 2 \times 2 \times 3 \times 2$ or 72 simulation runs. The same sets of random order interarrival and job processing times were used for each simulation run. To eliminate the initial transience, each simulation was run for 50,000 periods before 10 batch means of 50,000 periods each were collected.

7. Results

At a statistical significance of 0.01, a full factorial analysis of variances (ANOVA) was conducted for each performance measure, and Tukey's comparison was used to examine the significant interactions. The ANOVA results showed that the same main and interaction effects are statistically significant for each performance measure. It is therefore sufficient to tabulate only the ANOVA results for the mean customer wait time (CWT) in Table 3 for further discussion. Table 3 shows that all main effects are statistically significant, with the exception of the priority rule. Based on the size of mean square errors (MSE) in Table 3, the experimental factors can be ranked in the order of number of cards, withdrawal cycle, transfer policy, production control system, and priority rule, with the priority rule having the smallest impact on the performance measures.

The above ANOVA table also shows that many high-order interactions are statistically significant. A Tukey's comparison of the interactions showed that these high-order interactions do not affect the ordinal rankings of the factor levels beyond the second-order interactions. To report the performance of the production control systems and policy variables, it is therefore sufficient to present only the overall performance of the production control systems and their second-order interactions with each of the policy variables.

7.1. *Overall Performance of the Production Control Systems*

Table 4 summarizes the overall performance of the three production control systems for each of the seven performance criteria. Each cell mean is an average performance of a specific production control system over 24 combinations of policy variables (2 priority rules, 2 levels of number of cards, 3 levels of withdrawal cycles, and 2 transfer policies). The table shows that production control systems significantly affect the performance. The control logic on the flow of cards and containers, therefore, affects the performance significantly.

TABLE 2

Experimental Design

Factors	Number of Levels	Factor Levels
Production Control System (PC)	3	SK, DK, and CW
Priority Rule (PR)	2	FCFS and MNC
Number of Cards (NC)	2	Small and large
Withdrawal Cycle (WC)	3	2, 4, and 6 periods
Transfer Policy (TP)	2	IT (Immediate) and PT (Periodic)

TABLE 3
ANOVA Results for Mean Customer Wait Time (*CWT*)

Source	DF	Mean Square Errors	F Value	Pr > F
PC	2	529.85421189	1,491.82	0.0001
PR	1	0.45937462	1.29	0.2558
NC	1	6,944.90817852	19,553.62	0.0001
WC	2	3,375.68233694	9,504.35	0.0001
TP	1	2,970.60333459	8,363.83	0.0001
PC × PR	2	0.15337761	0.43	0.6495
PC × NC	2	484.13708517	1,363.10	0.0001
PC × WC	4	287.75473726	810.18	0.0001
PC × TP	2	56.49085948	159.05	0.0001
PR × NC	1	0.18587732	0.52	0.4697
PR × WC	2	0.03778726	0.11	0.8991
PR × TP	1	0.22670813	0.64	0.4246
NC × WC	2	3,202.22241250	9,015.97	0.0001
NC × TP	1	2,865.44904195	8,067.77	0.0001
WC × TP	2	1,775.65720909	4,999.42	0.0001
PC × PR × NC	2	0.11695263	0.33	0.7196
PC × PR × WC	4	0.01036160	0.03	0.9984
PC × PR × TP	2	0.13338737	0.38	0.6871
PC × NC × WC	4	267.40231235	752.88	0.0001
PC × NC × TP	2	53.12465944	149.57	0.0001
PC × WC × TP	4	44.29849533	124.72	0.0001
PR × NC × WC	2	0.05056781	0.14	0.8673
PR × NC × TP	1	0.23242952	0.65	0.4188
PR × WC × TP	2	0.07744727	0.22	0.8041
NC × WC × TP	2	1,730.81334554	4,873.16	0.0001
PC × PR × NC × WC	4	0.01633162	0.05	0.9960
PC × PR × NC × TP	2	0.09004482	0.25	0.7761
PC × PR × WC × TP	4	0.02173873	0.06	0.9931
PC × TP × NC × WC	4	43.79106967	123.30	0.0001
PR × NC × WC × TP	2	0.15396613	0.43	0.6484
PC × PR × NC × WC × TP	4	0.06078633	0.17	0.9531

With the least restrictive control on the flow of cards and containers, Conwip performs extremely well across all performance measures. It produces the smallest mean customer wait time, total work-in-process, and total number of trips between stations. Relative to the Dual-kanban, Conwip produces not only a mean reduction of 37% in the mean customer wait time, but also mean reductions of 28 and 3% in the total work-in-process and total number of trips between stations, respectively.

With a less restrictive control logic than that of the Dual-kanban, the Single-kanban also produces a shorter mean customer wait time, but a larger total work-in-process and total number of trips than the Dual-kanban. Relative to the Dual-kanban, the Single-kanban reduces the mean customer wait time by 20% but increases the total work-in-process and total

TABLE 4
Mean Performance of Production Control Systems

PC	CWT	IWIP	OWIP	TWIP	NUT	NDT	TNT
CW	5.086	35.577	3.220	38.797	0.267	1.906	2.173
SK	6.470	51.139	3.238	54.378	1.082	1.910	2.992
DK	8.056	27.491	26.243	53.734	1.088	1.247	2.250

TABLE 5

Interaction Between Priority Rule and Production Control System

PR	PC	CWT	IWIP	OWIP	TWIP	NUT	NDT	TNT
MNC	CW	5.036	35.570	3.222	38.791	0.267	1.905	2.173
	SK	6.444	51.155	3.238	54.394	1.082	1.910	2.992
	DK	8.056	27.517	26.216	53.734	1.088	1.247	2.335
FCFS	CW	5.136	35.584	3.218	38.802	0.268	1.907	2.174
	SK	6.496	51.124	2.238	54.362	1.082	1.910	2.991
	DK	8.055	27.465	26.270	53.735	1.088	1.253	2.341

number of trips by 1 and 33%, respectively. The overall performance of the production control systems should, however, be interpreted with care since their performance is by affected the policy variables.

7.2. *Effect of Priority Rules*

Table 5 tabulates the performance of the production control systems against the two priority rules. Consistent with the ANOVA results in Table 3, Table 5 shows that priority rules affect the performance of each production control system very slightly. Conwip, for example, produces a mean customer wait time of 5.036 and 5.136 periods when MNC and FCFS priority rules are used, respectively. This result is consistent with Ardalan's study (1997), which showed that priority rules have the smallest impact on the performance of a Dual-kanban flow line compared with factors such as the number of cards and withdrawal cycle. Our result, however, extends Ardalan's (1997) finding. It shows that the impact of priority rules is small regardless of the chosen production control system.

In general, the MNC priority rule always produces a slightly smaller mean customer wait time, total work-in-process, and total number of trips than the FCFS priority rule. The improvements are, however, statistically insignificant. Consequently, the MNC priority rule is preferred for its slightly better performance, while the FCFS priority rule is preferred for its simplicity as a priority rule.

7.3. *Effect of Number of Cards*

Table 6 shows the effects of changing the number of cards on the performance of each production control system. Increasing the number of cards reduces the mean customer wait time and increases the total work-in-process significantly. Increasing the number of cards also has an interesting effect on the number of upstream and downstream trips. A larger number of cards allows a larger number of containers to be moved per trip, which in turn reduces the numbers of upstream, downstream, and total number of trips between stations. These reductions in the number of trips are, however, very small with the exception of Dual-kanban. When the number of cards is increased, the Dual-kanban reports significant

TABLE 6

Interaction Between Number of Cards and Production Control System

NC	PC	CWT	IWIP	OWIP	TWIP	NUT	NDT	TNT
Large	CW	3.359	50.567	3.214	53.781	0.267	1.906	2.173
	SK	3.445	75.205	3.226	78.431	1.079	1.908	2.988
	DK	3.491	40.292	37.898	78.191	1.081	1.159	2.240
Small	CW	6.814	20.587	3.226	23.812	0.267	1.907	2.174
	SK	9.495	27.074	3.250	30.324	1.084	1.911	2.995
	DK	12.620	14.690	14.588	29.278	1.096	1.341	2.437

reductions of 1.4, 15.7, and 8.8% in the number of upstream, downstream, and total number of trips, respectively.

Table 6 also shows that the number of cards does not affect the ordinal ranking of the production control systems in each performance measure. Conwip continues to produce the smallest mean customer wait time, total work-in-process, and total number of trips between stations. The Single-kanban also continues to produce a shorter mean customer wait time, but a larger total work-in-process and total number of trips between stations than the Dual-kanban.

Increasing the number of cards, however, reduces the absolute differences in the mean customer wait time among the production control systems, although their ordinal ranking is unaffected. Relative to the Dual-kanban, Conwip produces a significant mean reduction of 46% in the mean customer wait time when the number of cards is small, but a mere mean reduction of 4% in the mean customer wait time when the number of cards is large. At both levels of number of cards, Conwip continues to produce a better customer service than the Single-kanban and Dual-kanban, with a significantly lower total work-in-process.

The results also show that changing the number of cards affects the output work-in-process differently. While the output work-in-process of Conwip and Single-kanban decreases slightly by about 1%, the output work-in-process of Dual-kanban increases significantly by 160% when the number of cards is increased. To explain the contrasting effect on the output work-in-process, we suggested that a larger number of cards produces a smoother flow of replenished containers from the output storage points to the input storage points, which reduces the output work-in-process of Conwip and Single-kanban. However, when the number of cards is increased for the Dual-kanban, it causes a proportional increase in the numbers of withdrawal cards and production cards for the Dual-kanban. The increased number of production cards, in turn, sets a higher upper limit on the number of full containers that can be retained at the Dual-kanban's output storage points, increasing its output work-in-process significantly.

7.4. *Effect of Withdrawal Cycle*

Table 7 tabulates the interaction between the production control system and the withdrawal cycle. The results show that changing the withdrawal cycle produces a similar effect on each production control system. Increasing the withdrawal cycle increases the mean customer wait time, but reduces the total work-in-process, number of upstream trips, number of downstream trips, and total number of trips between stations.

Table 7 shows that a longer withdrawal cycle reduces the number of upstream transfers of withdrawal cards. This slower upstream transfer of withdrawal cards, in turn, increases the possibility of station blocking because of the delayed transfer of incoming withdrawal cards to authorize the starts of production. A longer withdrawal cycle also reduces the number of

TABLE 7

Interaction Between Withdrawal Cycle and Production Control System

WC	PC	CWT	IWIP	OWIP	TWIP	NUT	NDT	TNT
2	CW	3.632	38.300	1.538	39.838	0.396	2.152	2.548
	SK	3.933	57.623	1.550	59.173	1.616	2.166	3.782
	DK	3.946	31.315	27.617	58.932	1.629	1.746	3.375
4	CW	4.262	35.629	3.202	38.831	0.240	1.857	2.097
	SK	5.029	51.256	3.219	54.475	0.967	1.857	2.824
	DK	5.577	27.536	26.362	53.899	0.972	1.143	2.115
6	CW	7.366	32.802	4.919	37.721	0.165	1.710	1.875
	SK	10.448	44.540	4.946	49.485	0.663	1.706	2.369
	DK	14.645	23.622	24.750	48.372	0.664	0.861	1.525

downstream transfers of replenished containers. This slower transfer of replenished containers, in turn, increases the possibility of station starvation because of the absence of raw materials at the input storage points. A longer withdrawal cycle therefore increases the mean customer wait time, but reduces the total work-in-process because of a slower production and movement of work-in-process.

The results also show that, as the withdrawal cycle is altered, the distribution of the total work-in-process between the input and output storage points is affected by the choice of the production control system. When the Dual-kanban is used, reducing the withdrawal cycle increases the input and output work-in-process simultaneously. This happens because a shorter withdrawal cycle speeds up the production and accumulation of full containers (with attached production cards) at the output storage points. At the same time, a shorter withdrawal cycle also speeds up the movement and accumulation of full containers (with attached withdrawal cards) at the input storage points.

However, when Conwip or Single-kanban is used, reducing the withdrawal cycle increases the input work-in-process, but reduces the output work-in-process. This happens because both Conwip and Single-kanban attach a withdrawal card to each full container produced at a station. Consequently, when the immediate transfer (IT) policy is used, any increased numbers of replenished containers (produced by the shorter withdrawal cycle) are transferred immediately to the input storage points. Similarly, when the periodic transfer (PT) policy is used, the shorter withdrawal cycle also ensures that most of the replenished containers are transferred frequently to the input storage points. These faster movements of replenished containers from the output to input storage points therefore reduce the output work-in-process and increase the input work-in-process.

Table 7 also indicates some slight interactions between the production control system and the withdrawal cycle on the mean customer wait time and total work-in-process. While the ranking of the production control systems on the mean customer wait time and total work-in-process remains the same at each withdrawal cycle, their absolute differences become smaller as the withdrawal cycle is reduced. The withdrawal cycle also does not affect the ranking of the production control systems on the number of upstream trips. The different systems can be ranked as Conwip, Single-kanban, and Dual-kanban, with Conwip generating the smallest number of upstream trips.

While the withdrawal cycle does not affect the ranking of the production control systems on the mean customer wait time, total work-in-process, and number of upstream trips, the withdrawal cycle affects the ranking of the production control systems on the number of downstream trips and total number of trips. These interactions will be discussed in Section 7.5 together with the effect of the transfer policy, which also affects the ranking of the production control systems on the number of downstream trips and total number of trips.

7.5. *Effect of Transfer Policy*

Table 8 tabulates the interaction between the production control system and the transfer

TABLE 8

Interaction Between Transfer Policy and Production Control System

TP	PC	CWT	IWIP	OWIP	TWIP	NUT	NDT	TNT
IT	CW	3.586	38.807	0.0	38.807	0.267	2.755	3.022
	SK	4.328	54.493	0.0	54.493	1.081	2.752	3.834
	DK	5.604	27.847	26.332	54.179	1.089	1.419	2.507
PT	CW	6.587	32.347	6.439	38.787	0.267	1.057	1.324
	SK	8.612	47.786	6.477	54.263	1.082	1.067	2.149
	DK	10.507	27.135	26.154	53.289	1.088	1.081	2.169

policy. Similar to the withdrawal cycle, the transfer policy does not affect the ranking of the production control systems on the mean customer wait time, total work-in-process, and number of upstream trips. Conwip continues to produce the smallest mean customer wait time, total work-in-process, and number of upstream trips. Similarly, the Single-kanban produces a smaller mean customer wait time and number of upstream trips, but a larger total work-in-process than the Dual-kanban.

Table 8 shows that the IT policy consistently produces a significantly shorter mean customer wait time, but a slightly higher total work-in-process than the PT policy regardless of the choice of the production control system. While the differences in the number of upstream trips between the IT and PT policies are statistically insignificant, the IT policy generates a significantly larger number of downstream trips, which smoothes the production and movement of work-in-process. The IT policy therefore produces a better customer service at a cost of a larger number of downstream trips and a slightly higher total work-in-process.

Table 8 also shows that the output storage points of Conwip and Single-kanban are always empty when the IT policy is used. This happens because both Conwip and Single-kanban attach a withdrawal card to each full container produced at a station. Consequently, once a full container is produced, the IT policy allows an immediate transfer of the full container (with the attached withdrawal card) to the input storage point of the next downstream station, resulting in zero work-in-process at the output storage points at all times.

Similar to the effect of the withdrawal cycle, Table 8 shows that the transfer policy affects the ranking of the production control systems on the number of downstream trips and total number of trips. To analyze the interactions among the withdrawal cycle, transfer policy, and production control system, Figures 1 and 2 plot these interactions on the number of downstream trips and total number of trips, respectively.

Figure 1 shows that the transfer policy affects the ranking of the production control systems on the number of downstream trips. When the IT policy is used in Figure 1a, the Dual-kanban produces the smallest number of downstream trips across all withdrawal cycles; while Conwip and Single-kanban produce significantly larger numbers of downstream trips. In contrast, when the PT policy is used in Figure 1b, the differences in the number of downstream trips among the production control systems become statistically insignificant; and the ranking of the production control systems is reversed with Conwip generating the smallest and Dual-kanban generating the largest number of downstream trips. In Figure 1, a and b, the withdrawal cycle does not affect the ranking of the production control systems on the number of downstream trips.

Figure 2 plots the interaction among the withdrawal cycle, transfer policy, and production control system on the total number of trips. When the IT policy is used in Figure 2a, the Dual-kanban produces the smallest total number of trips at the longer withdrawal cycles of four and six periods, while Conwip produces the smallest total number of trips at the withdrawal cycle of two periods. In contrast, when the PT policy is used in Figure 2b, Conwip consistently produces the smallest total number of trips, while the Single-kanban and Dual-kanban produce significantly larger total numbers of trips.

As a summary of the above results, Table 9 tabulates the ranking of the production control systems under the effect of the two policy variables that significantly affect the choice of the production control systems. The two policy variables are the transfer policy and the withdrawal cycle. Table 9 tabulates the best and worst performing production control systems as the first and second entries in each cell. When the PT policy is used, Conwip produces the smallest mean customer wait time, total work-in-process, and total number of trips. However, when the IT policy is used, Conwip produces the smallest mean customer wait time and total work-in-process, but not necessarily the smallest total number of trips when the withdrawal cycle is long.

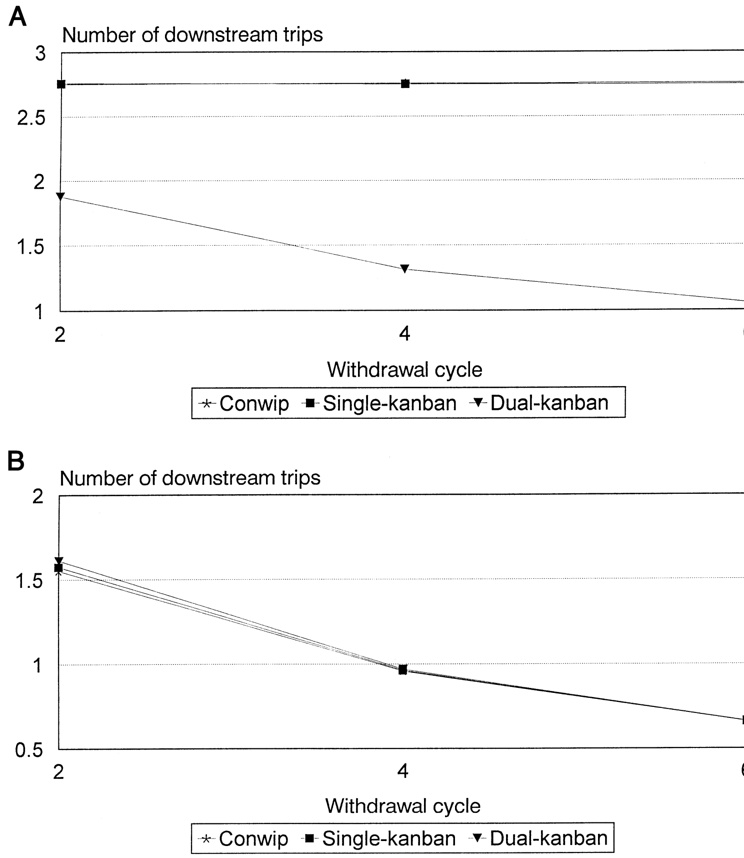
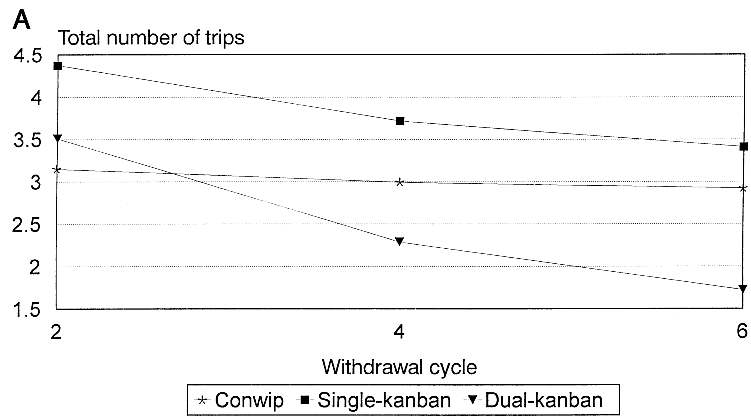


FIGURE 1A. Number of Downstream Trips With IT Policy.
FIGURE 1B. Number of Downstream Trips With PT Policy.

8. Conclusions

Past literature has suggested the Single-kanban, Dual-kanban, and Conwip for managing a multi-product flow line without any rigorous comparison. This paper therefore rigorously compares the Single-kanban, Dual-kanban, and Conwip, with four other policy variables for managing a multi-product flow line. The policy variables are the priority rule, number of cards, withdrawal cycle, and transfer policy. The results produce several useful guidelines on choosing the right production control system and policy variables.

The effects of the experimental factors on the mean customer wait time and total work-in-process can be ranked in the order of number of cards, withdrawal cycle, transfer policy, production control system, and priority rule, with the priority rule having the smallest impact. While increasing the number of cards, reducing the withdrawal cycle, and transferring full containers (with attached withdrawal cards) immediately to downstream stations reduce the mean customer wait time, these factor levels also increase the total work-in-process. Specifically, increasing the number of cards reduces the mean customer wait time, number of upstream trips, and number of downstream trips, but increases the total work-in-process. A shorter withdrawal cycle also reduces the mean customer wait time but increases the total work-in-process, number of upstream trips, and number of downstream trips. A transfer policy of moving full containers (with attached withdrawal cards) immediately, instead of periodically, to downstream stations also reduces the mean customer wait time, but increases the total work-in-process and number of downstream trips. Choosing the right



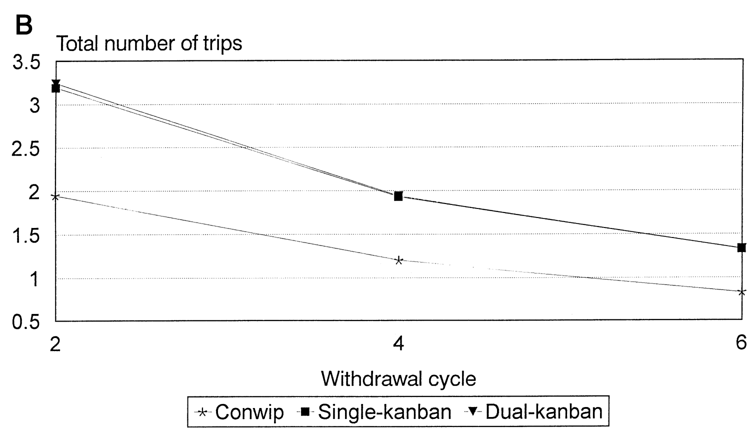


FIGURE 2A. Total Number of Trips With IT Policy.
FIGURE 2B. Total Number of Trips With PT Policy.

number of cards, withdrawal cycle, and transfer policy therefore requires a compromise between the levels of customer service, total work-in-process, and total number of trips between stations.

TABLE 9

Choosing the Right Production Control System

	Transfer Policy			
	Immediate Transfer		Periodic Transfer	
Withdrawal Cycle	Short	Long	Short	Long
Customer wait time	Conwip*	Conwip	Conwip	Conwip
	Dual-kanban†	Dual-kanban	Dual-kanban	Dual-kanban
Total work-in-process	Conwip	Conwip	Conwip	Conwip
	Single-kanban	Single-kanban	Single-kanban	Single-kanban
Total number of trips	Conwip	Dual-kanban	Conwip	Conwip
	Single-kanban	Single-kanban	Dual-kanban	Dual-kanban

* The best performer.
† The worst performer.

While our results indicate that production control systems and priority rules have a smaller impact on the mean customer wait time and total work-in-process than the other policy variables, choosing the right production control system and priority rule can improve both the mean customer wait time and total work-in-process simultaneously. Our results show that Conwip consistently produces the smallest mean customer wait time, total work-in-process, and number of upstream trips. The maximum number of cards priority rule also consistently produces a smaller mean customer wait time, total work-in-process, and total number of trips than the first-come, first-served priority rule, although the differences are statistically insignificant. These findings are important and suggest that future research could investigate other production control systems and priority rules to further improve customer service and total inventory simultaneously.

Our results also show that the absolute performance differences among the production control systems and priority rules are affected by the other three policy variables. A larger number of cards, a shorter withdrawal cycle or transferring full containers (with attached withdrawal cards) immediately to downstream stations reduces the absolute differences in the mean customer wait time and total work-in-process among the production control systems and priority rules. While the other policy variables generally do not affect the ranking of the production control systems, the withdrawal cycle and transfer policy affect the ranking of the production control systems on the total number of trips. When the periodic transfer policy is used, Conwip requires the least total number of trips between stations. However, when the immediate transfer policy is used, the ranking of the production control systems on the total number of trips depends on the withdrawal cycle. When the immediate transfer policy is used, Conwip requires the smallest total number of trips when the withdrawal cycle is short while the Dual-kanban requires the smallest total number of trips when the withdrawal cycle is long.

Among the three production control systems, our results show that Conwip consistently produces the smallest mean customer wait and total work-in-process. This finding supports the assertion by Spearman, Woodruff, and Hopp (1990) that Conwip is a better system than Kanban. Conwip, however, has its own disadvantages. Our results show that Conwip does not always generate the smallest total number of trips between stations. Conwip may also require a larger storage space between alternate stations than the Single-kanban and Dual-kanban. In both the Single-kanban and Dual-kanban flow lines, the maximum storage space required between two alternate stations is determined precisely by the maximum number of cards circulating between the two stations. However, in a Conwip flow line, each withdrawal card is allowed to circulate through the entire line. Consequently, Conwip may require a larger storage space between alternate stations because all full containers (with attached withdrawal cards) may gather between any pair of alternate stations. Future research should therefore examine the effect of a limited storage space between alternate stations on the performance of a Conwip flow line.

References

ARDALAN, A. (1997), "Analysis of Local Decision Rules in a Dual-Kanban Flow Shop," *Decision Sciences*, 28, 1, 195–211.

BERKLEY, B. J. (1993), "Simulation Test of FCFS and SPT Sequencing Rules in Kanban System," *Decision Sciences*, 24, 1, 218–227.

——— AND A. S. KIRAN (1991), "A Simulation Study of Sequencing Rules in a Kanban-Controlled Flow Shop," *Decision Sciences*, 22, 3, 559–582.

HOPP, W. J. AND M. L. SPEARMAN (1996), *Factory Physics*: *Foundations of Manufacturing Management*, Irwin, Chicago, IL.

MONDEN, Y. (1983), *Toyota Production System*: *Practical Approach to Production Management*, Industrial Engineering and Production Management Press, Atlanta, GA.

MUCKSTADT, J. A. AND S. R. TAYUR (1995a), "A Comparison of Alternative Kanban Control Mechanisms. I. Background and Structural Results," *IIE Transactions*, 27, 2, 140–150.

——— AND ——— (1995b), "A Comparison of Alternative Kanban Control Mechanisms. II. Background and Structural Results," *IIE Transactions*, 27, 2, 151–161.

PRITSKER, A. A. B. (1986), *Introduction to Simulation and SLAM II* (3rd ed.), Halsted Press, New York.

SCHONBERGER, R. J. (1982), *Japanese Manufacturing Techniques*, Free Press, New York.

SPEARMAN, M. L., D. L. WOODRUFF, AND W. J. HOPP (1990), "Conwip: A Pull Alternative to Kanban," *International Journal of Production Research*, 28, 5, 879–894.

——— AND M. W. ZAZANIS (1992), "Push and Pull Production Systems: Issues and Comparison," *Operations Research*, 40, 3, 521–532.

WEMMERLOV, U. AND N. L. HYER (1989), "Cellular Manufacturing in the U.S. Industry: A Survey of Users," *International Journal of Production Research*, 27, 9, 1511–1530.

Kum Khiong Yang is an associate professor. He received his MBA and Ph.D. from Indiana University, Bloomington. His research interests have focused mainly on the design and analysis of service, manufacturing, and distribution systems. Some of his recent papers have appeared in journals such as *Naval Research Logistics*, *Production Planning and Control*, *Omega*, and *Decision Sciences*. He is a member of DSI and POMS.